Accumulation of Hydrogen-rich atmospheres onto the Earth and exo-Earths

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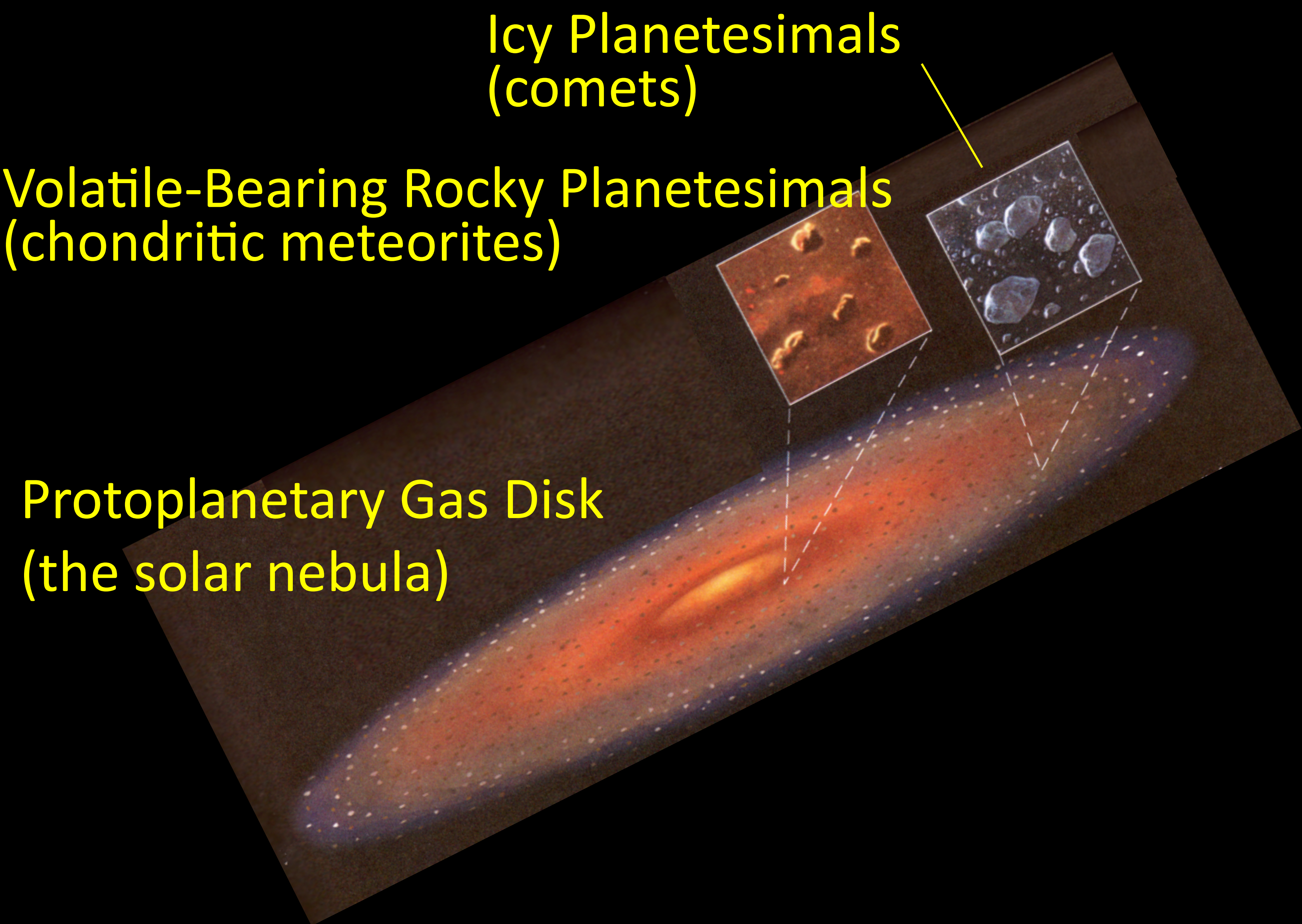
Possible Volatile Reservoirs in the Early Solar System



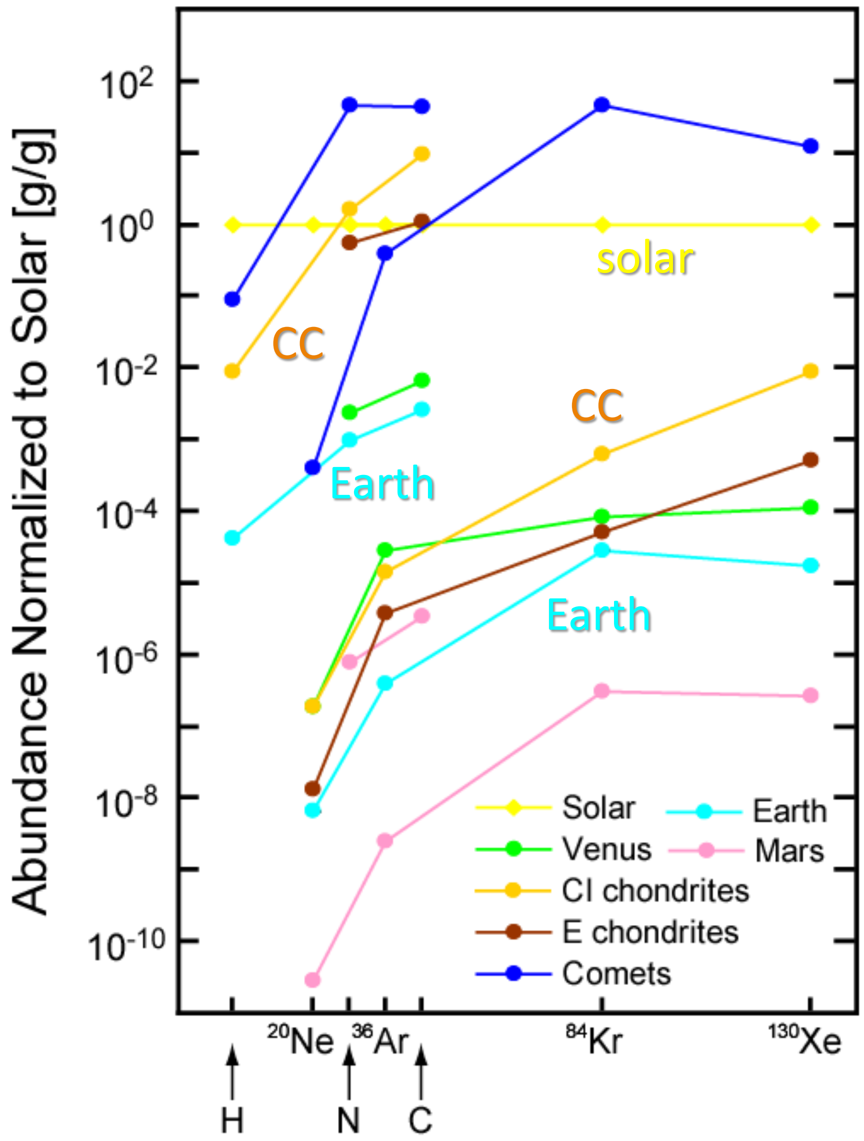
Origin of Earth's atmosphere

Unlikely to be gas
from the solar nebula

… ex.) *Noble gases are rare*

Probably delivered by
chondrites and/or *comets*

H2, N2, CO2, & noble gases

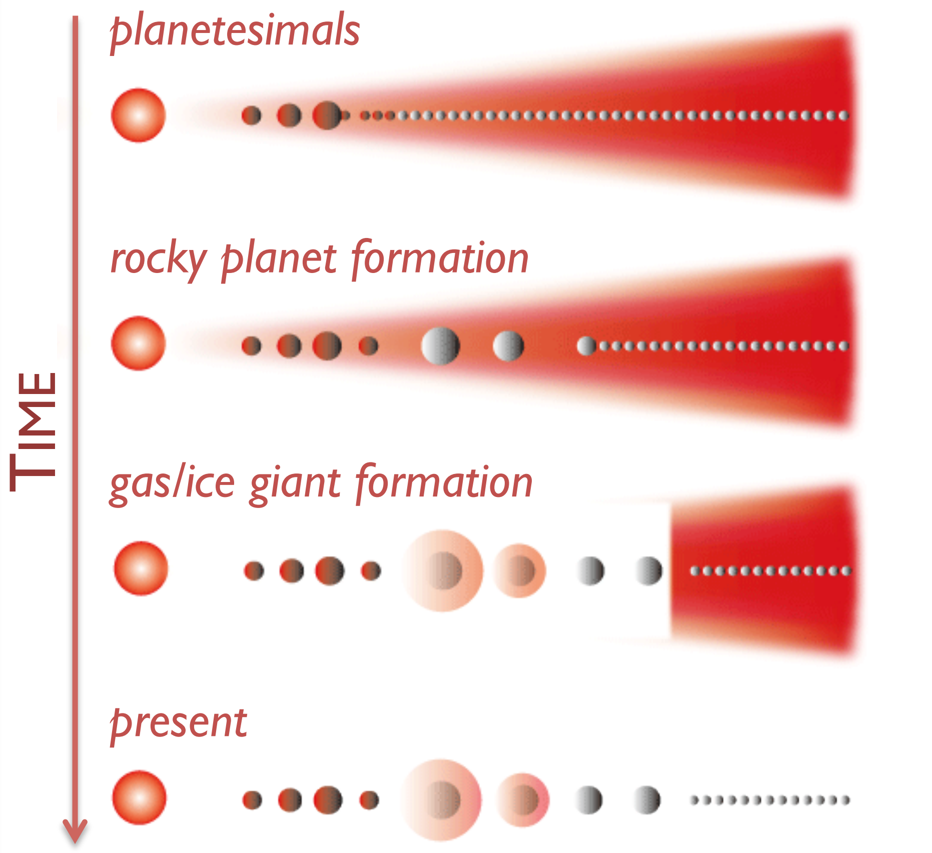


courtesy H. Genda

Hydrogen Atmosphere ...

A natural by-product of planet formation in the context of the core accretion model.

Planet formation occurs in a protoplanetary disk that is composed mainly of hydrogen.



But the Earth has no such hydrogen at present.

Questions

Did the Earth never get the disk gas?

Otherwise, was the primordial hydrogen completely lost?

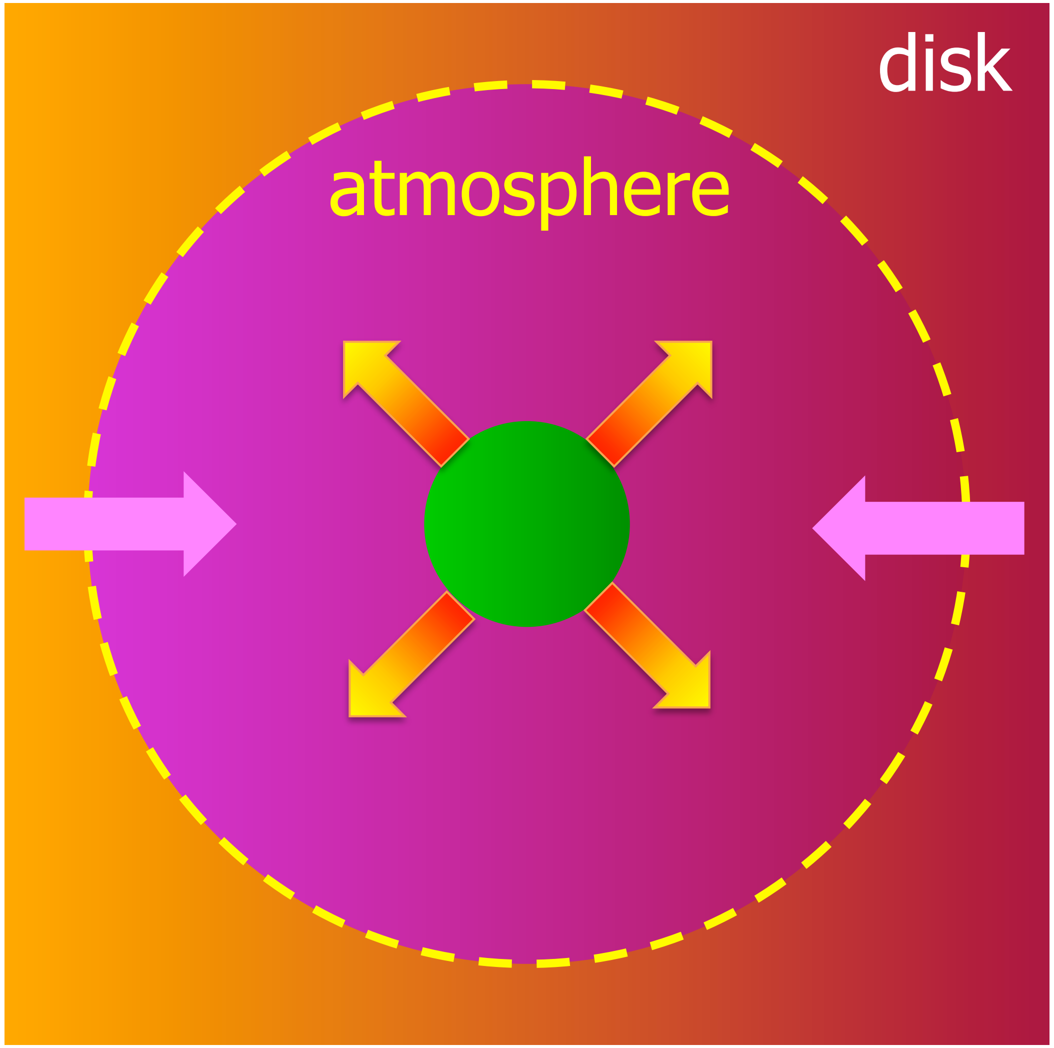
What are extrasolar Earth-like planets like?

Hydrogen Atmosphere …

- A natural by-product of planet formation in the context of the core accretion model.
- Causes degeneracy in composition of exoplanets with measured masses and radii.
- Produces sufficient amounts of water on planets.
- Affects the thermal and redox state which may be relevant to the origin and evolution of life.

Our objective is
to constrain how much hydrogen a planet obtains.

Accumulation of Atmosphere

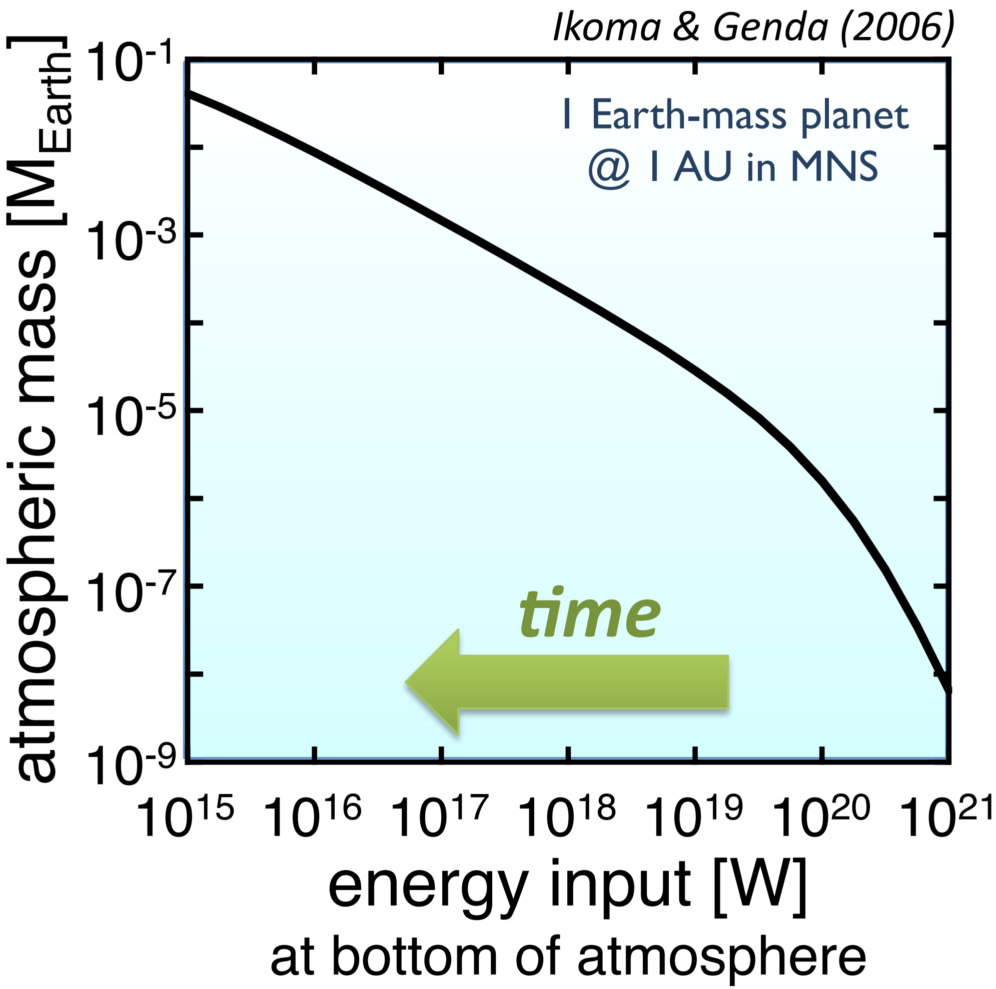


If embedded in
a protoplanetary gas disk,
a protoplanet has
an extended atmosphere.

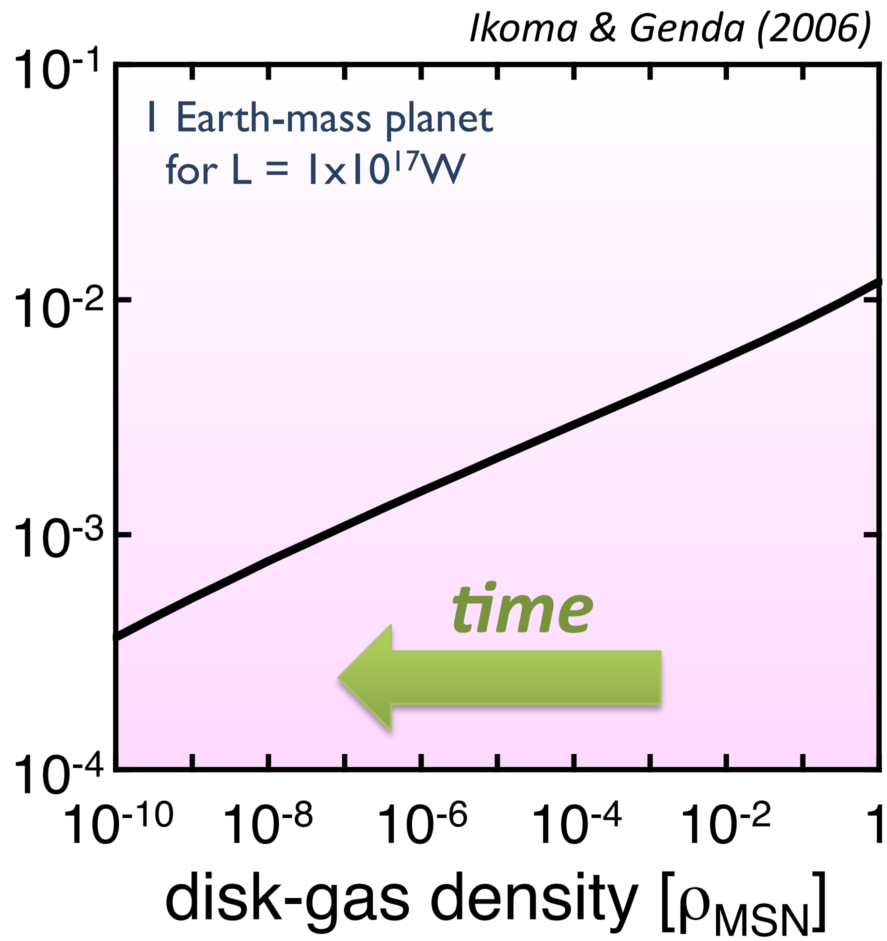
Contraction/expansion
of the atmosphere results in
gain/loss of mass.

Energy input
near the atmosphere's bottom
determines
the mass of the atmosphere

What Determines Atmospheric Mass



As energy input decreases, atmospheric mass increases.

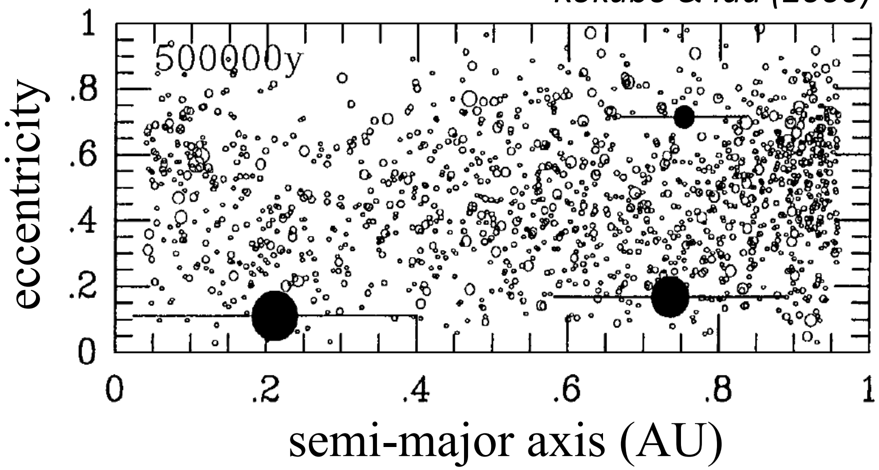


As disk density decreases, atmospheric mass decreases.

Accretion of Earth-analogs and super-Earths

Process for in-situ formation

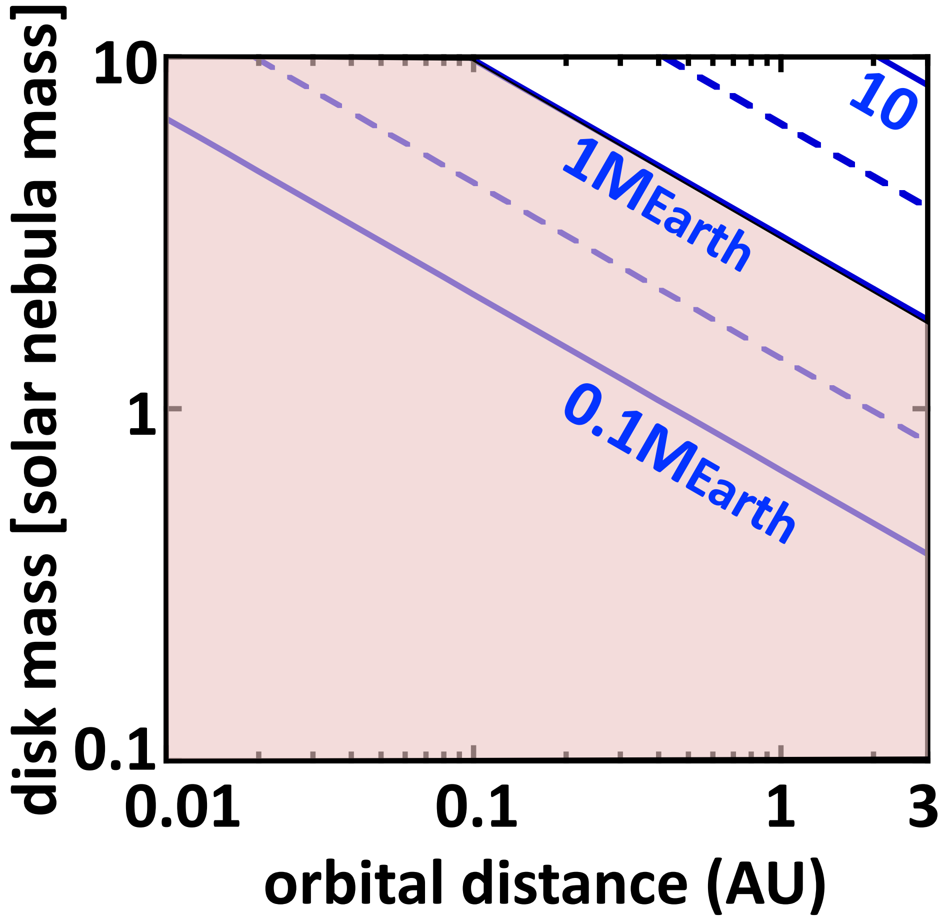
Kokubo & Ida (2000)



Continuous planetesimal bombardments are finished, when the protoplanet eats all planetesimals in its feeding zone.

In most of the inner disk,
the isolation mass is < 1 Earth mass.

An upper limit to the planet's mass
"isolation mass"

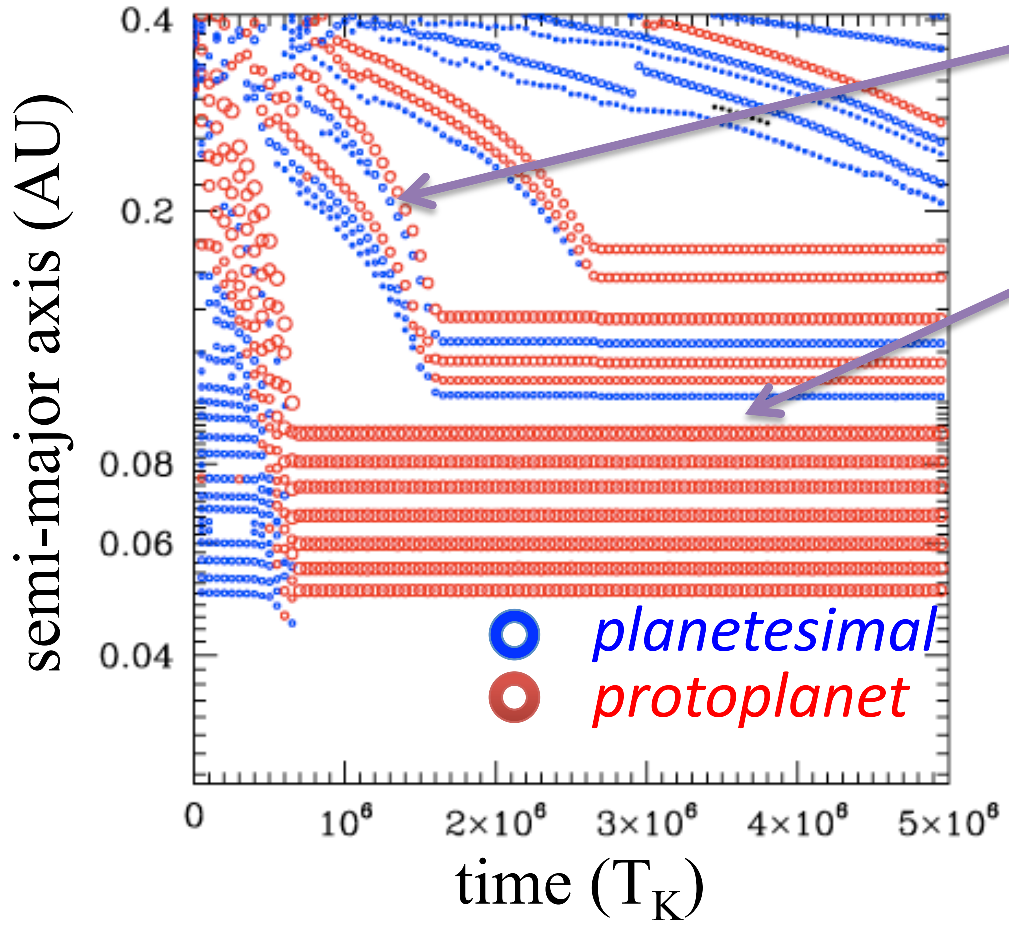


Earth analogs and super-Earths should experience giant collisions and/or migration.

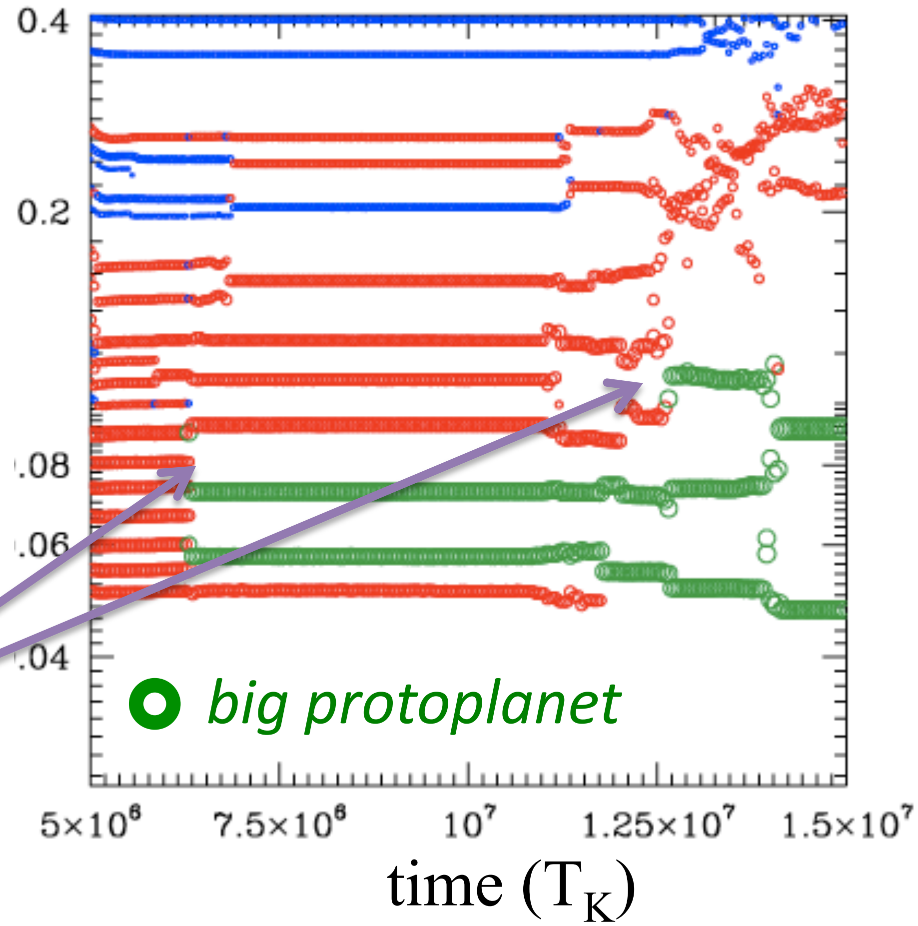
Accretion of Earth-Analogs and Super-Earths

Figures from Ogihara & Ida (2009)

M star

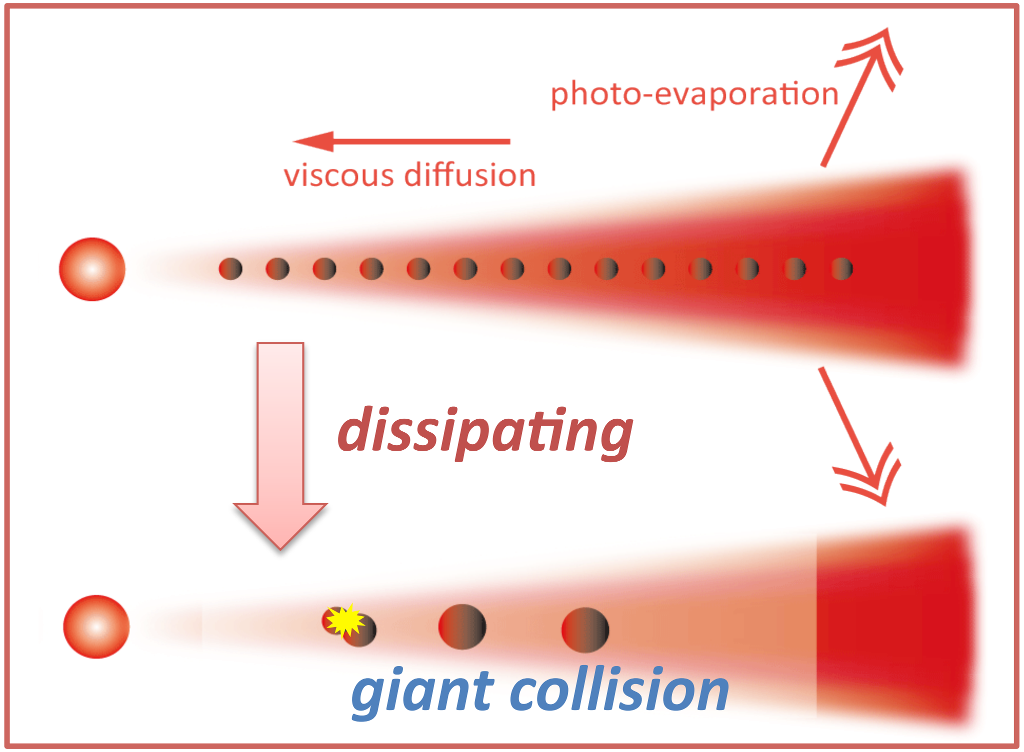


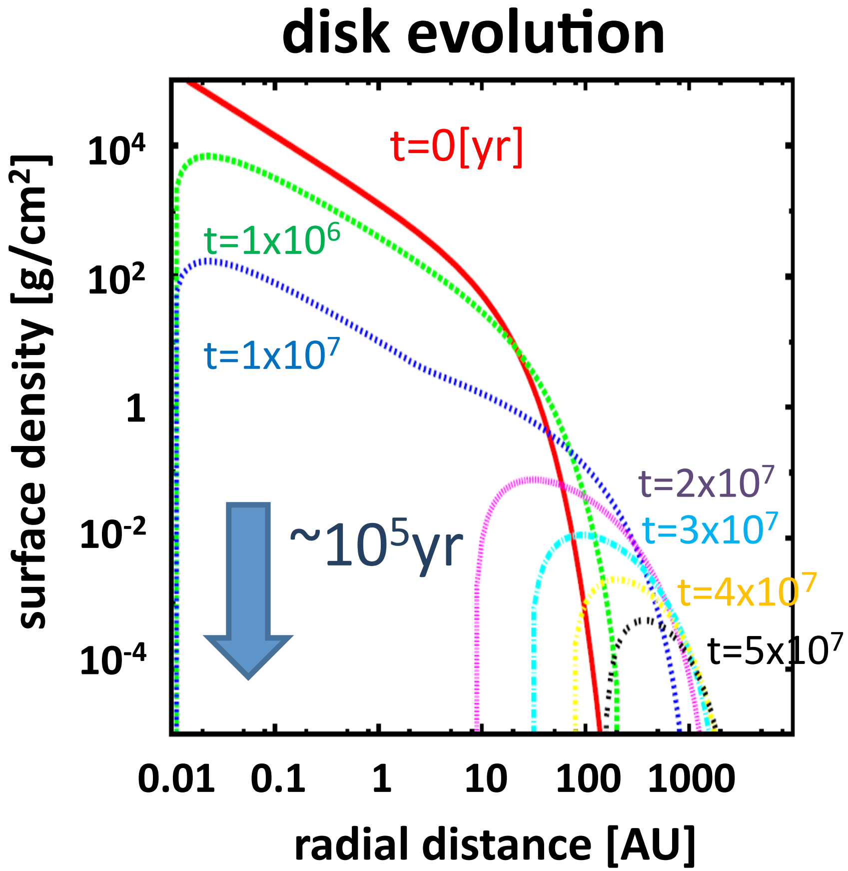
- *Protoplanets grow during inward migration*
- *Resonantly trapped*



Disk dissipation triggers orbital crossing and breaks resonant configuration.

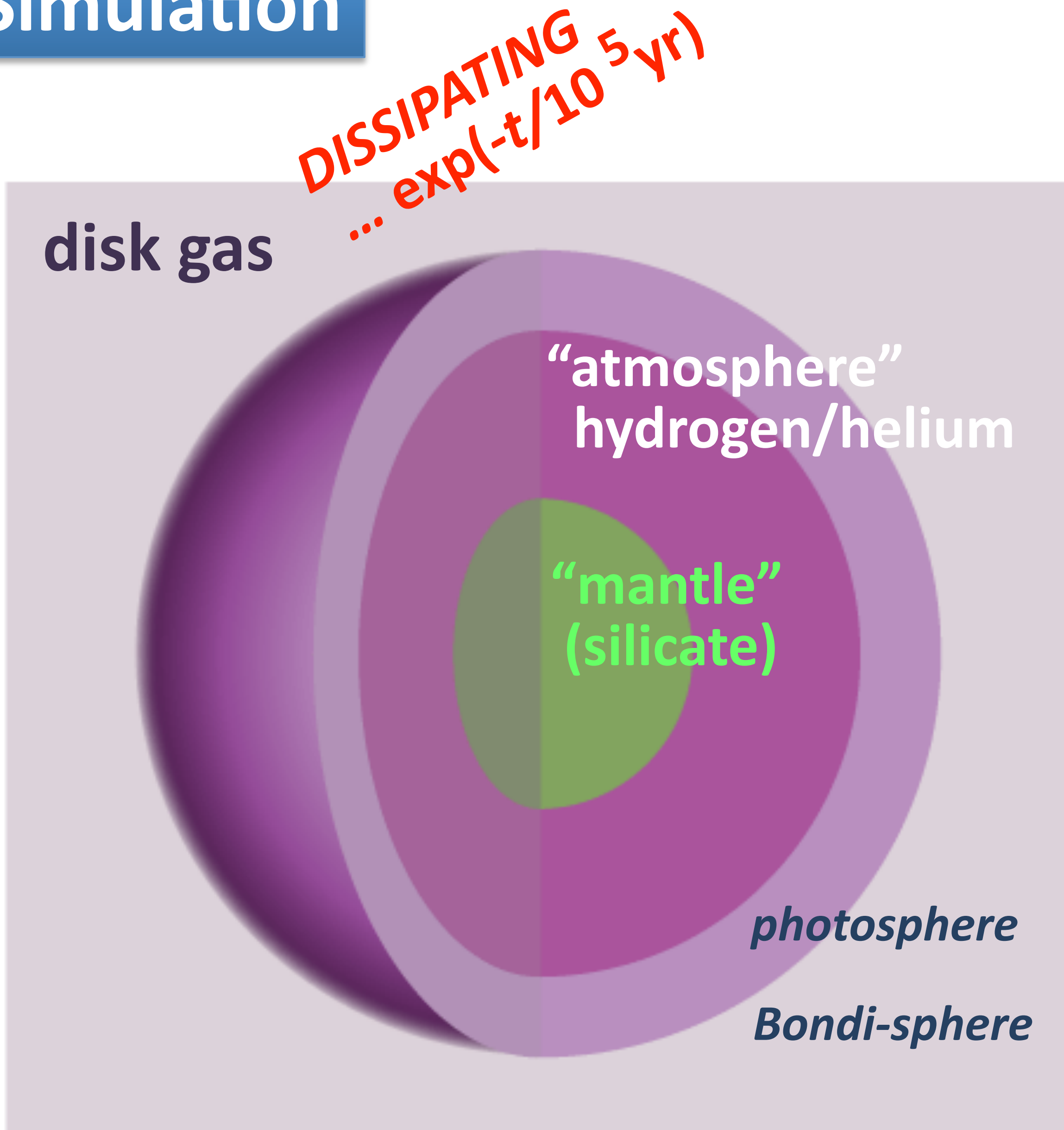
A Recent Picture for Disk Evolution





How a hydrogen atmosphere accumulates onto an isolated protoplanet after a giant impact in a dissipating disk ?

Simulation



<u>atmosphere:</u>

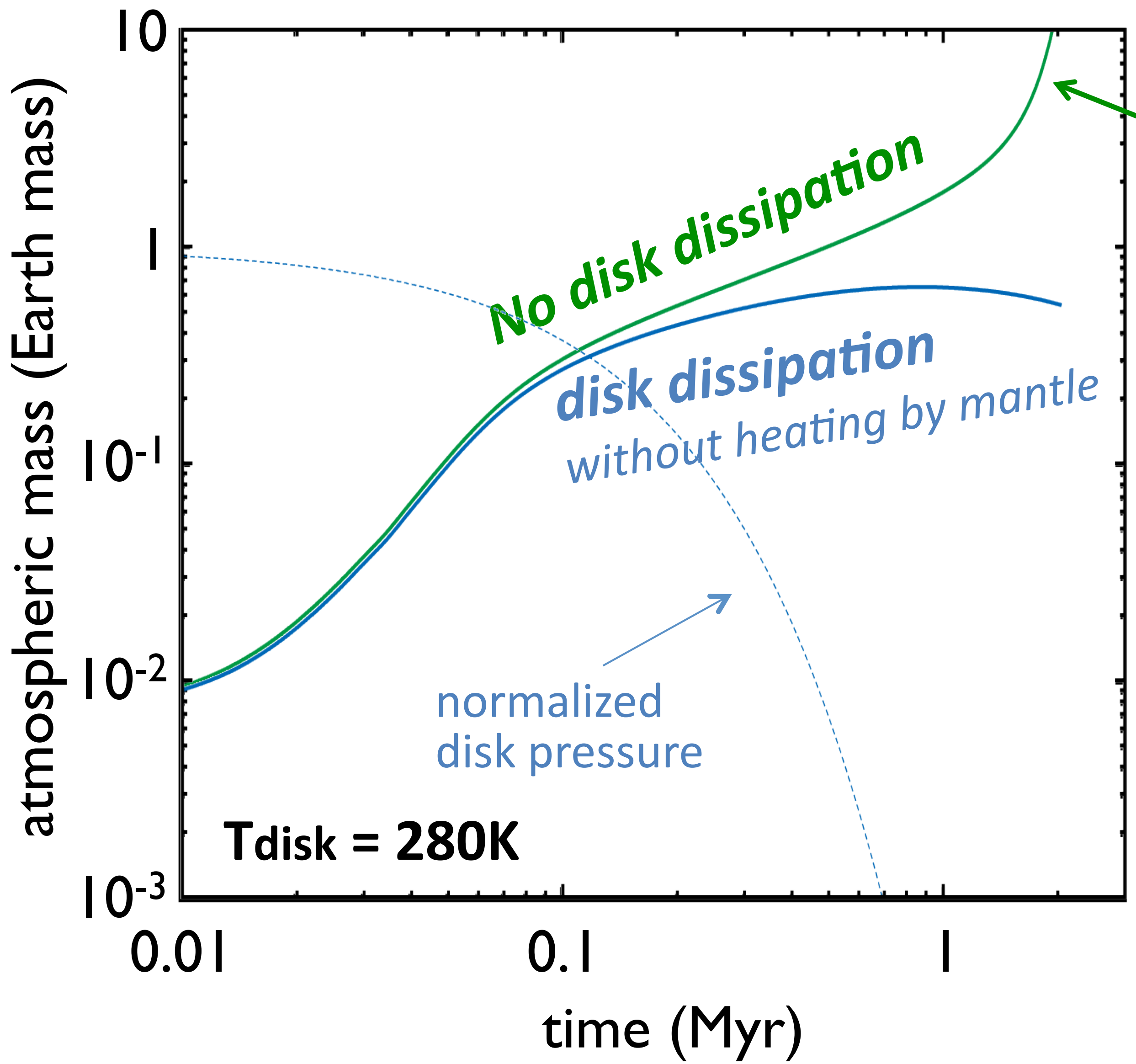
- SCvH EOS for H/He (Saumon+95)
- radiation/convection
- opacity
  - gas: Freedman+08
  - grain: 1/100 x Pollack+94

Cooling to heat atmosphere

<u>mantle:</u>

- Vinet EOS for $MgSiO_3$ with data from Mosenfelder+09
- convection
- liquid/solid

Atmosphere Accumulation: The Case of 5-Earth-mass planet



Runaway accretion
towards a gas giant

The growth **levels off** at ~ 1 Earth mass.

However,
the atmosphere does
not lose its mass.

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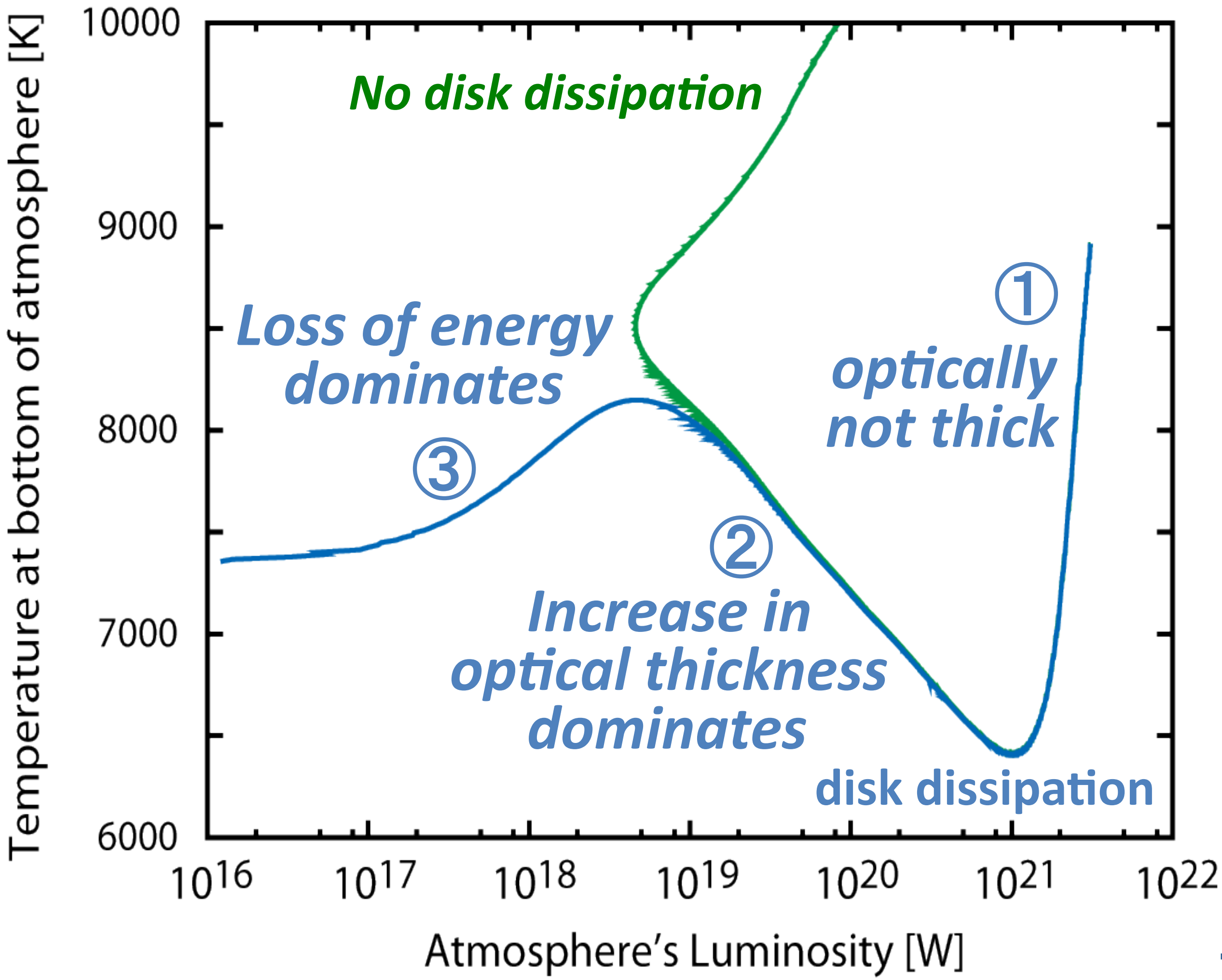
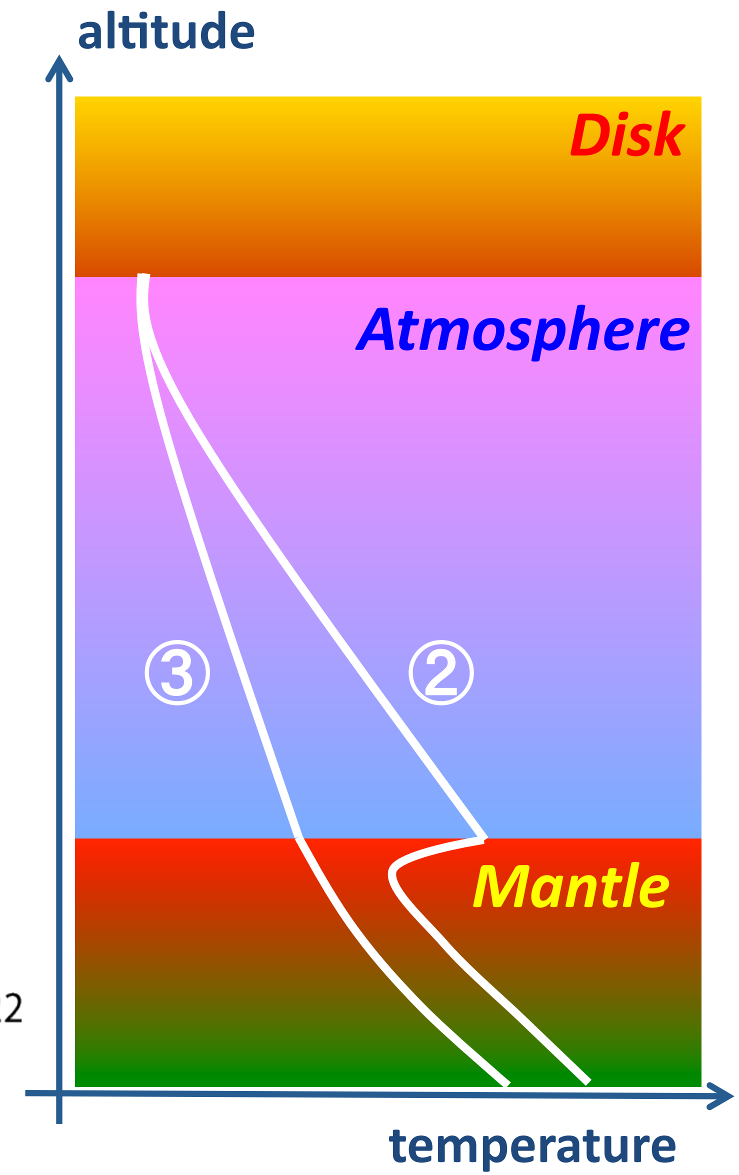
Blanketing Effect of the Atmosphere





TIME

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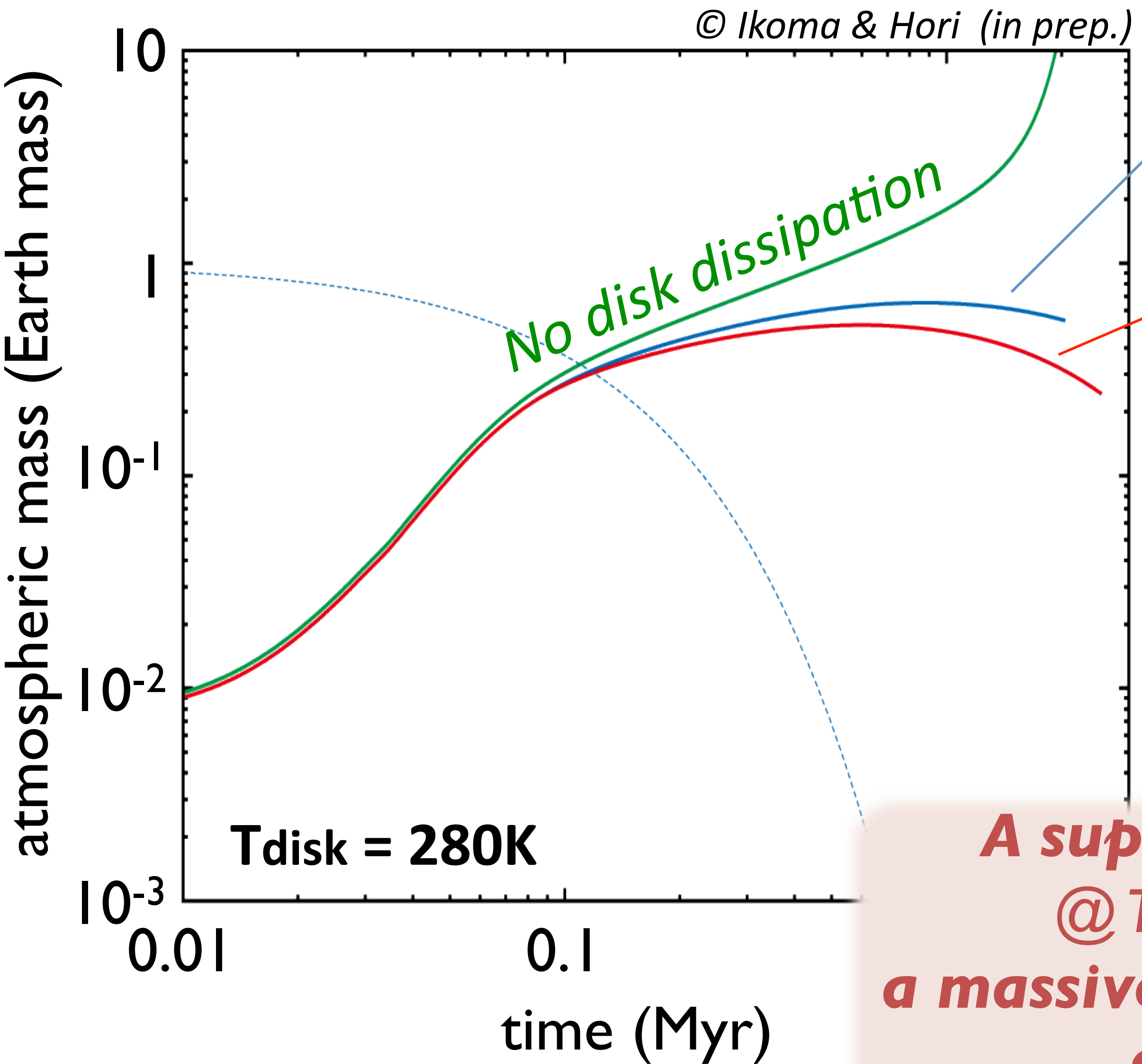
Atmosphere Accumulation: The Case of 5-Earth-mass planet



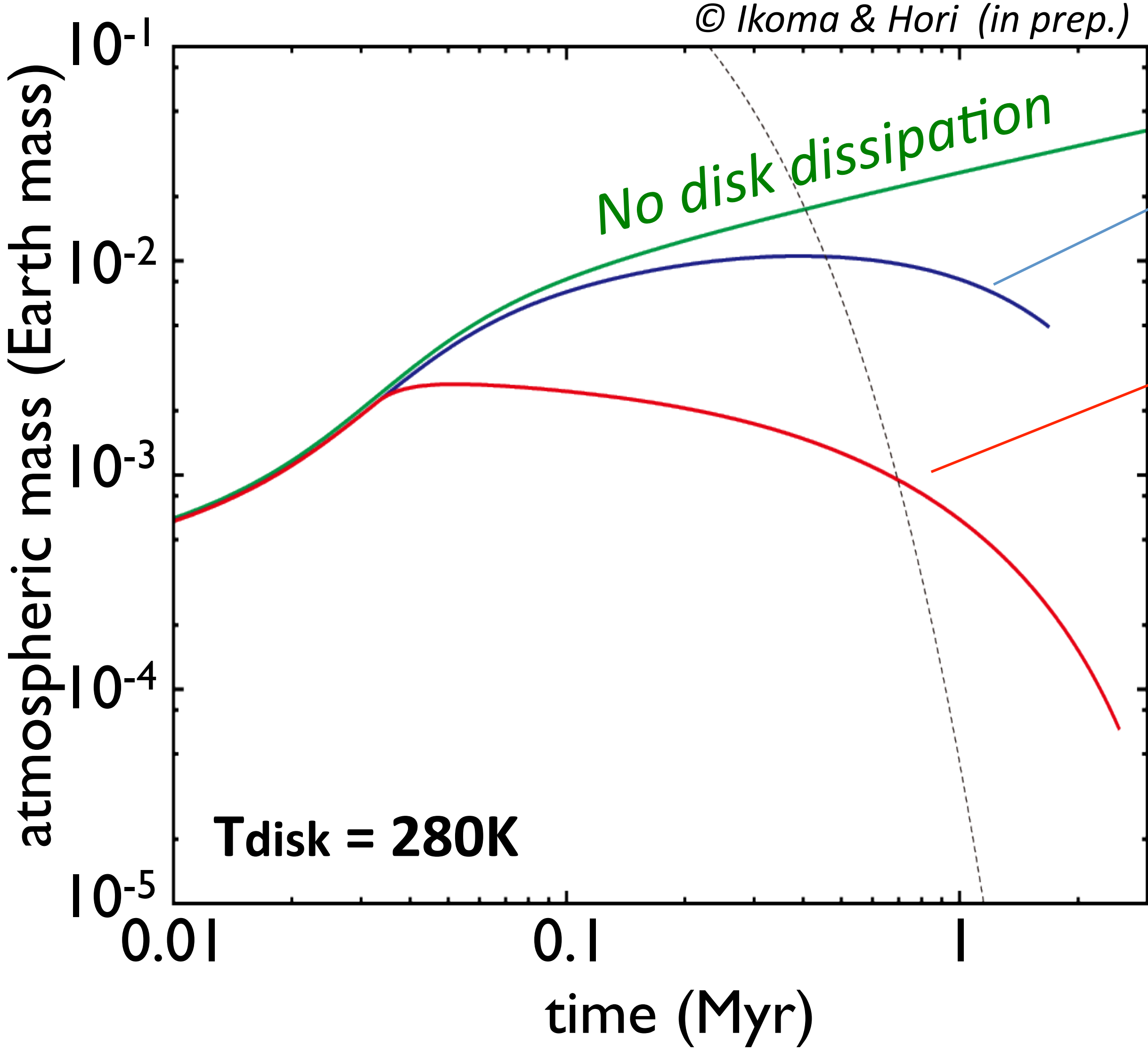
disk dissipation
without heating by mantle

disk dissipation
with heating by mantle

Mantle's contribution is small in this case…

A super-Earth of 5 M_{Earth}
@ T_{disk} = 280K ***obtains***
a massive hydrogen atmosphere
of ~ 0.1 M_{Earth}.

Atmosphere Accumulation: The Case of 1-Earth-mass planet



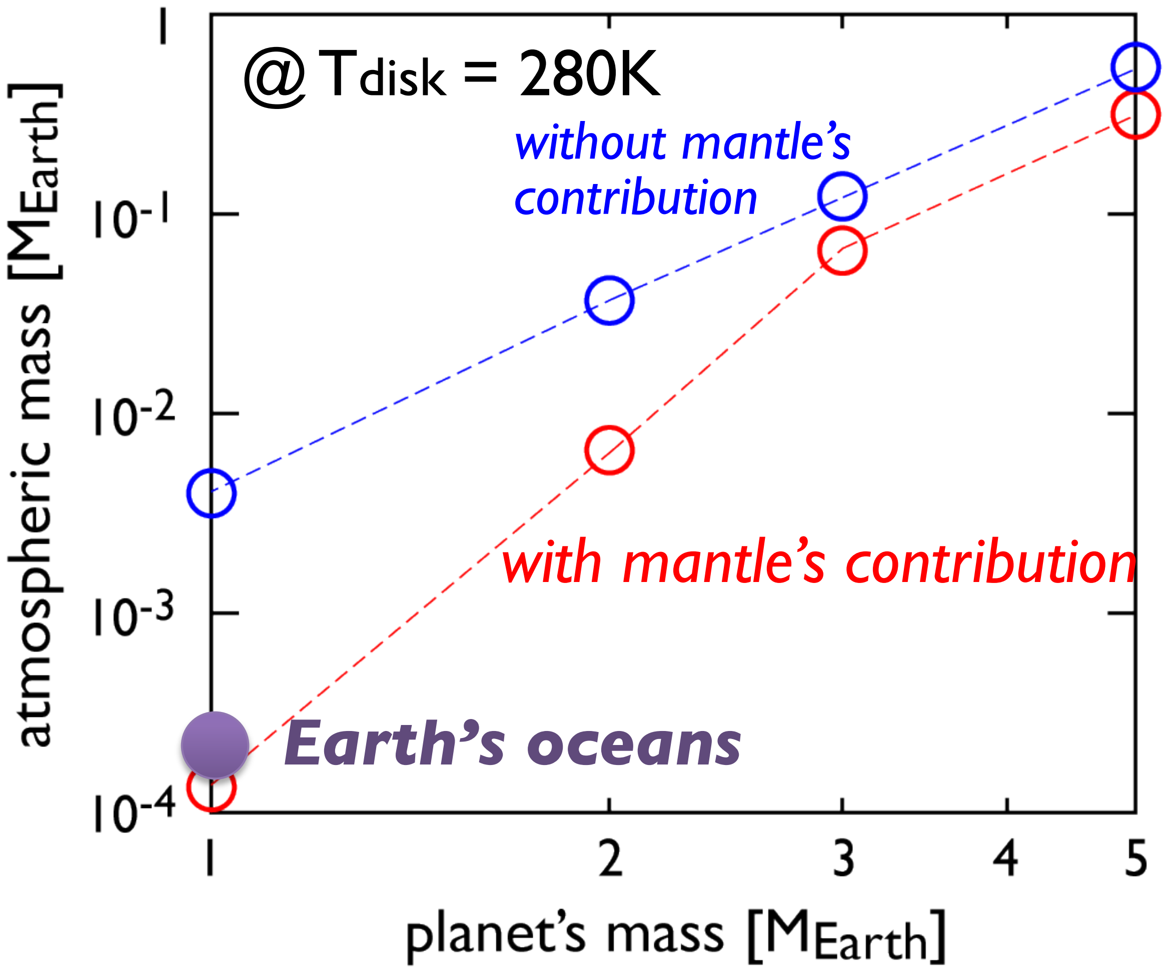
disk dissipation
without heating by mantle

disk dissipation
with heating by mantle

Heating by mantle is effective in removing a substantial amount of atmospheric gas

An Earth-analog *@ T_{disk} = 280K* ***obtains a hydrogen atmosphere of ~ 10^{-4} M_{Earth}.***

Dependence on Planetary Mass

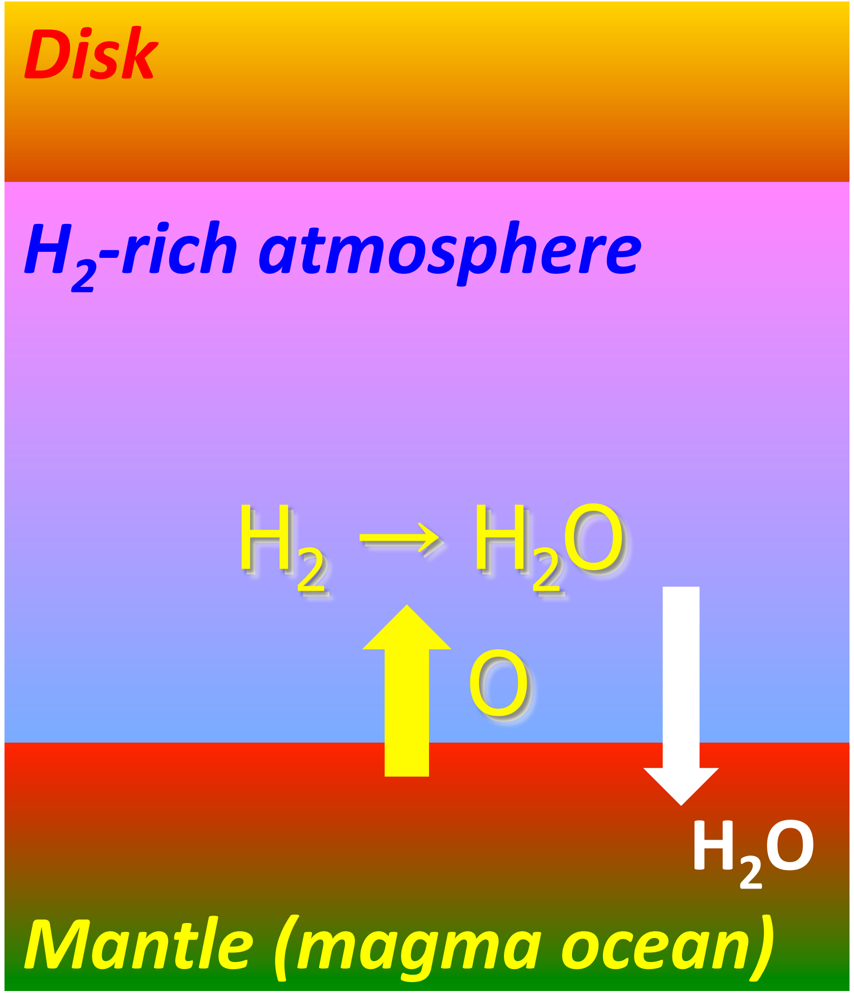


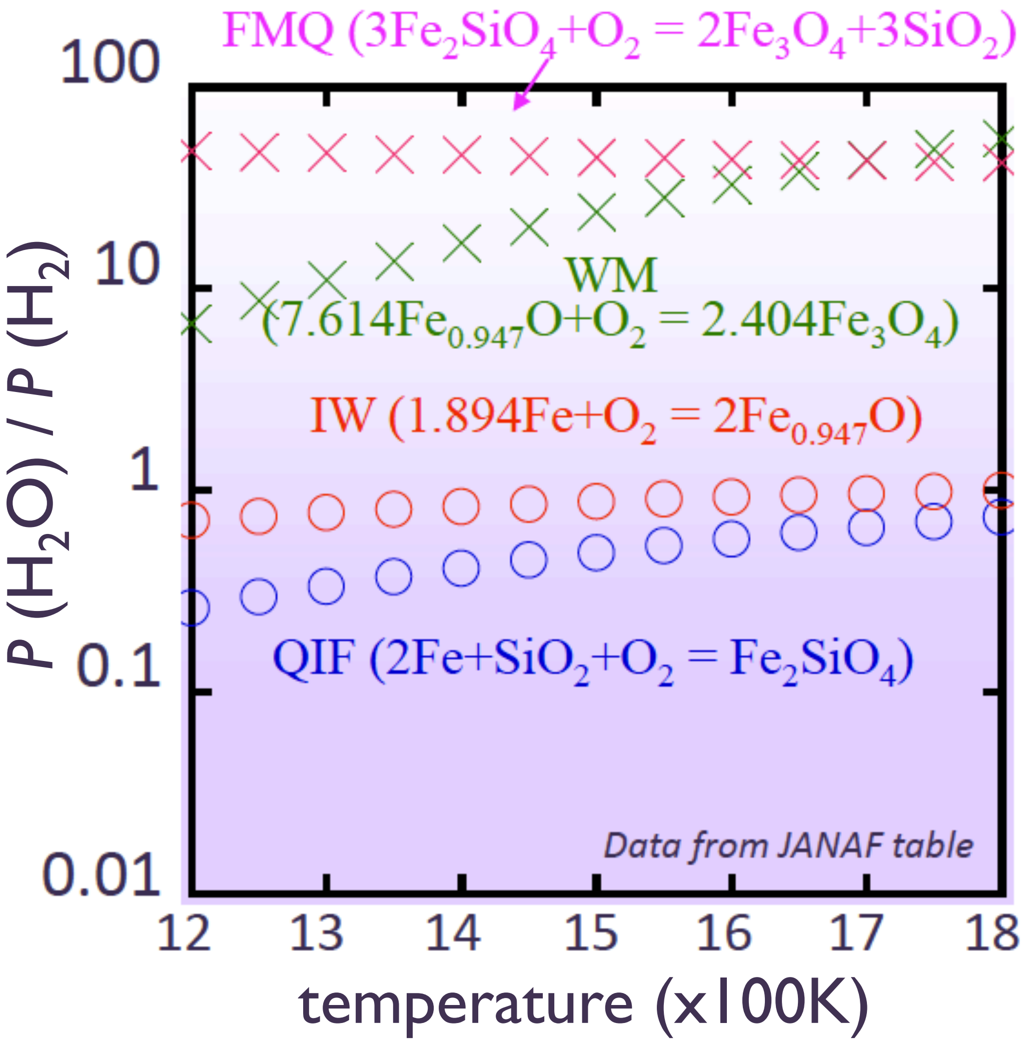
Strong dependence on the planet's mass

For low-mass planets, the thermal contribution from the mantle is effective in delaying atmosphere accumulation.

Earth-analogs and super-Earths** obtains hydrogen atmospheres **comparable** in mass **to or more massive than Earth's oceans.

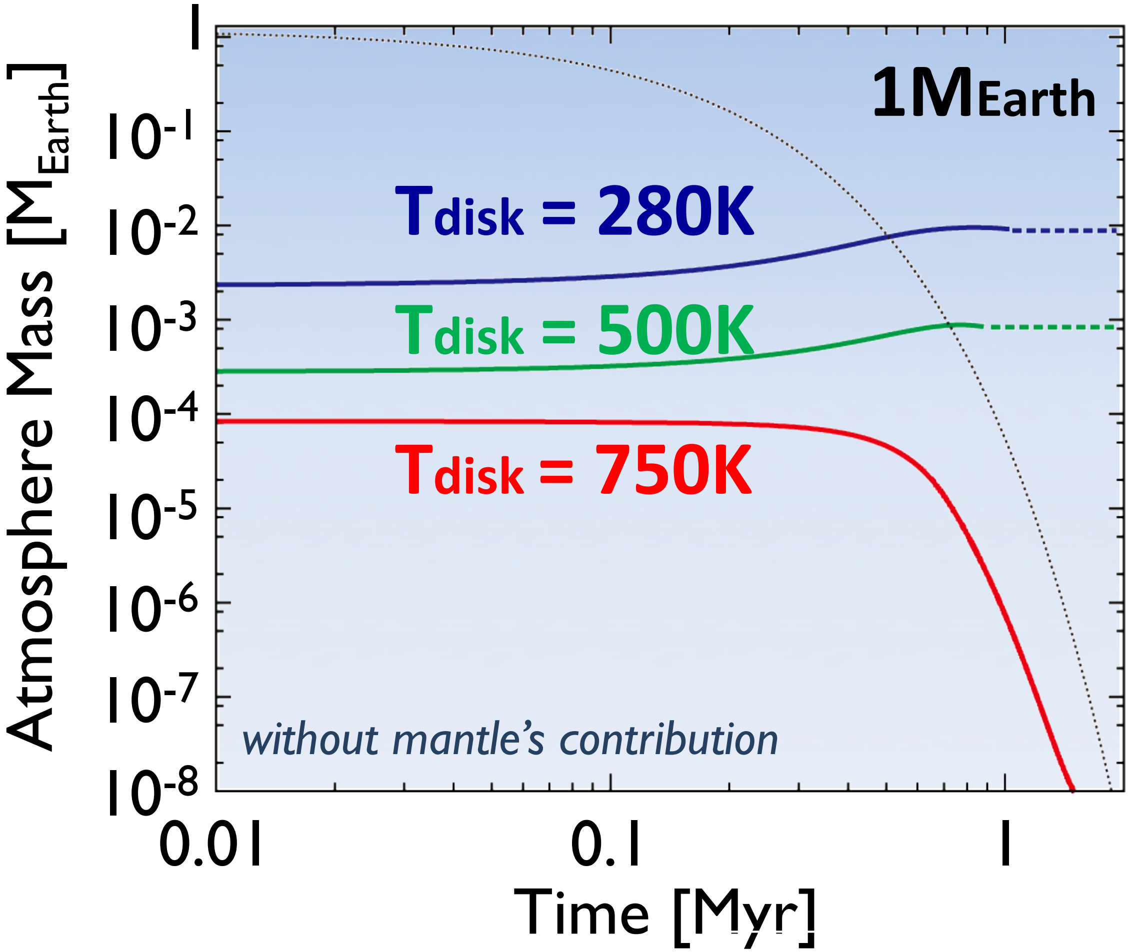
Water Production





- ***Water*** *comparable to or more than hydrogen* ***is produced.***
- ***Water is retained in the mantle.***

Sensitivity to Disk Temperature



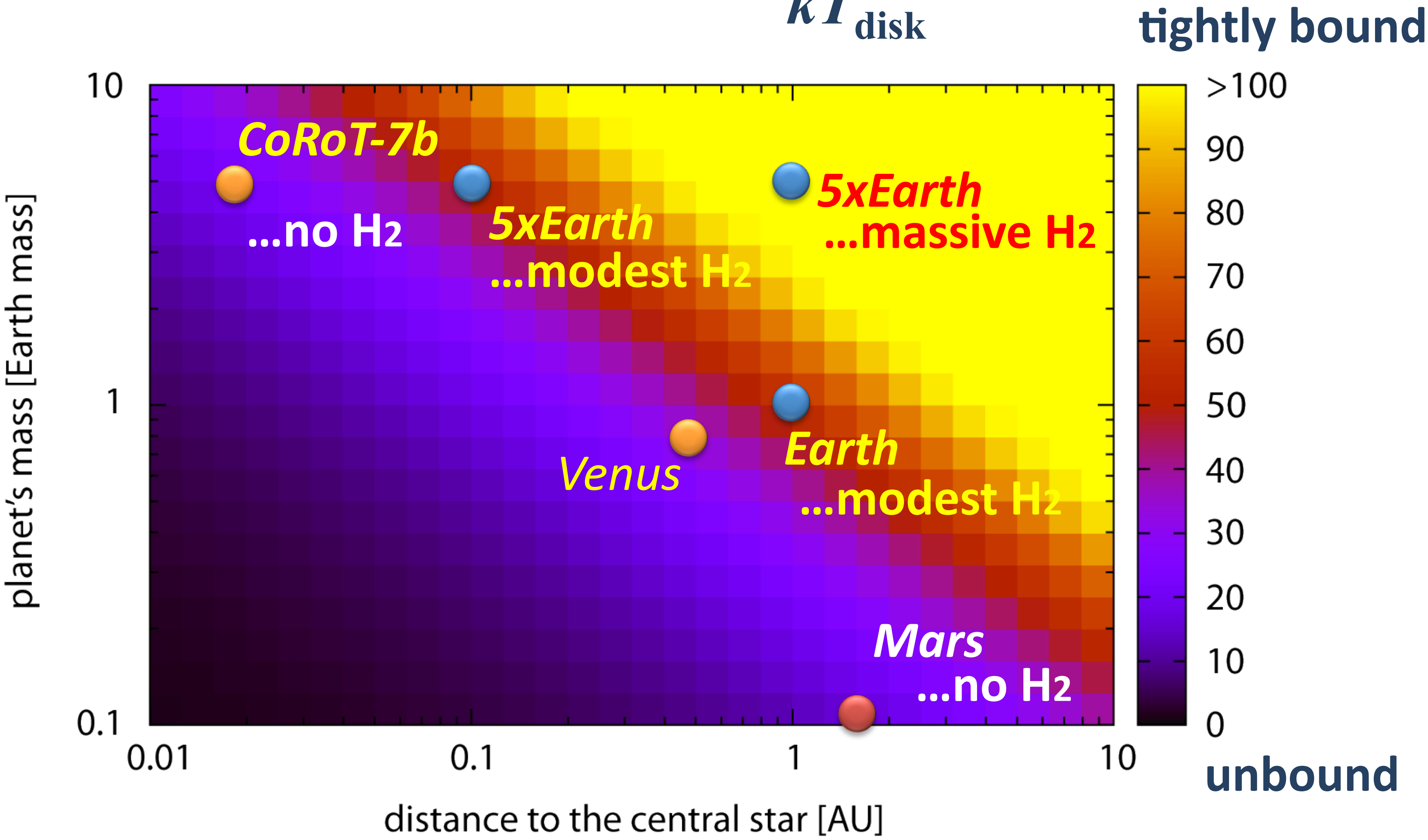
In extrasolar planetary systems, earth-like planets could be formed in various temperature environments.

750K is a threshold in this case, beyond which the atmosphere is removed by disk dissipation.

Sudden change in sensitivity to disk temperature

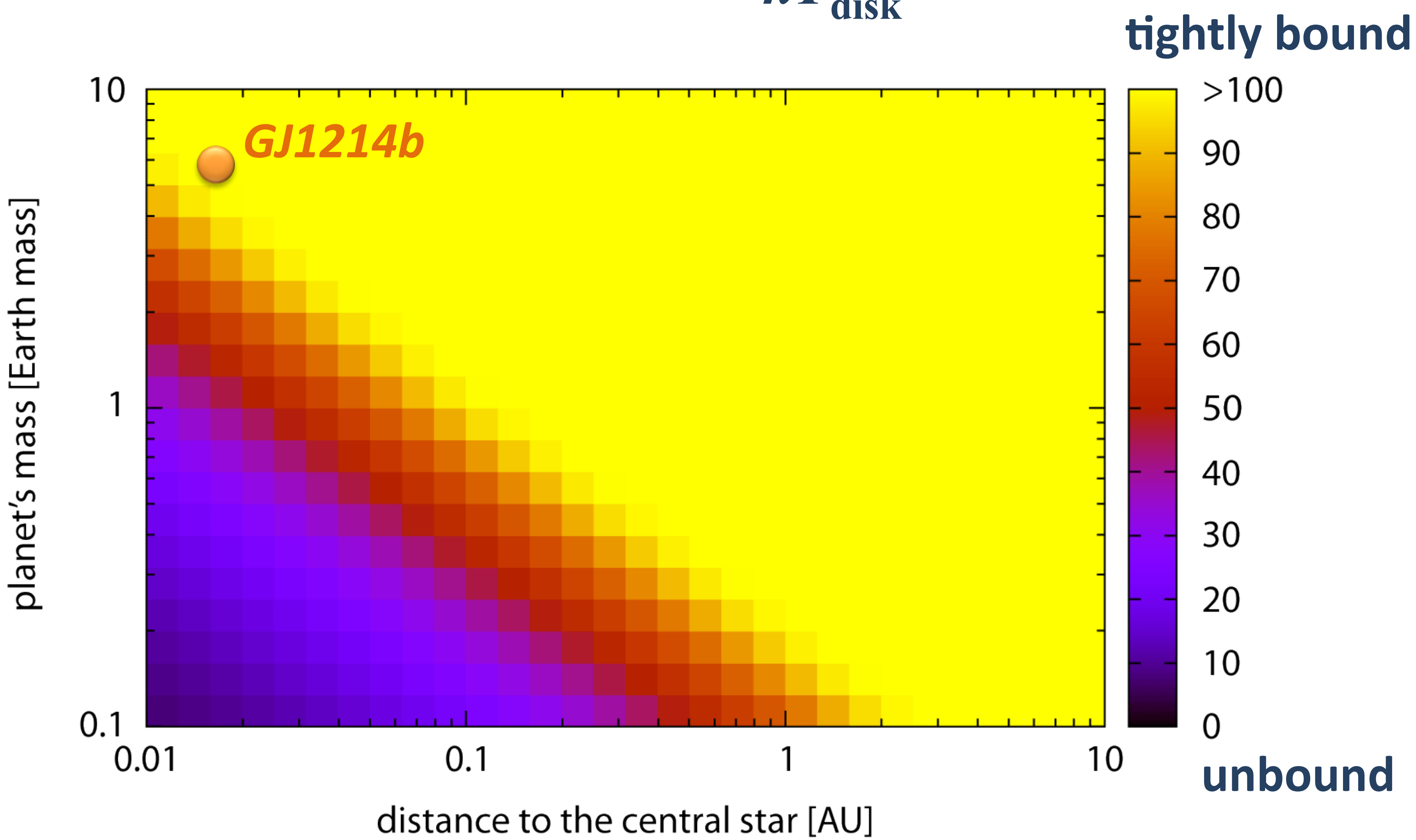
Close-In Super-Earths around G Stars

"escape" parameter: $\lambda = \dfrac{GM_p\mu}{kT_{disk}}$

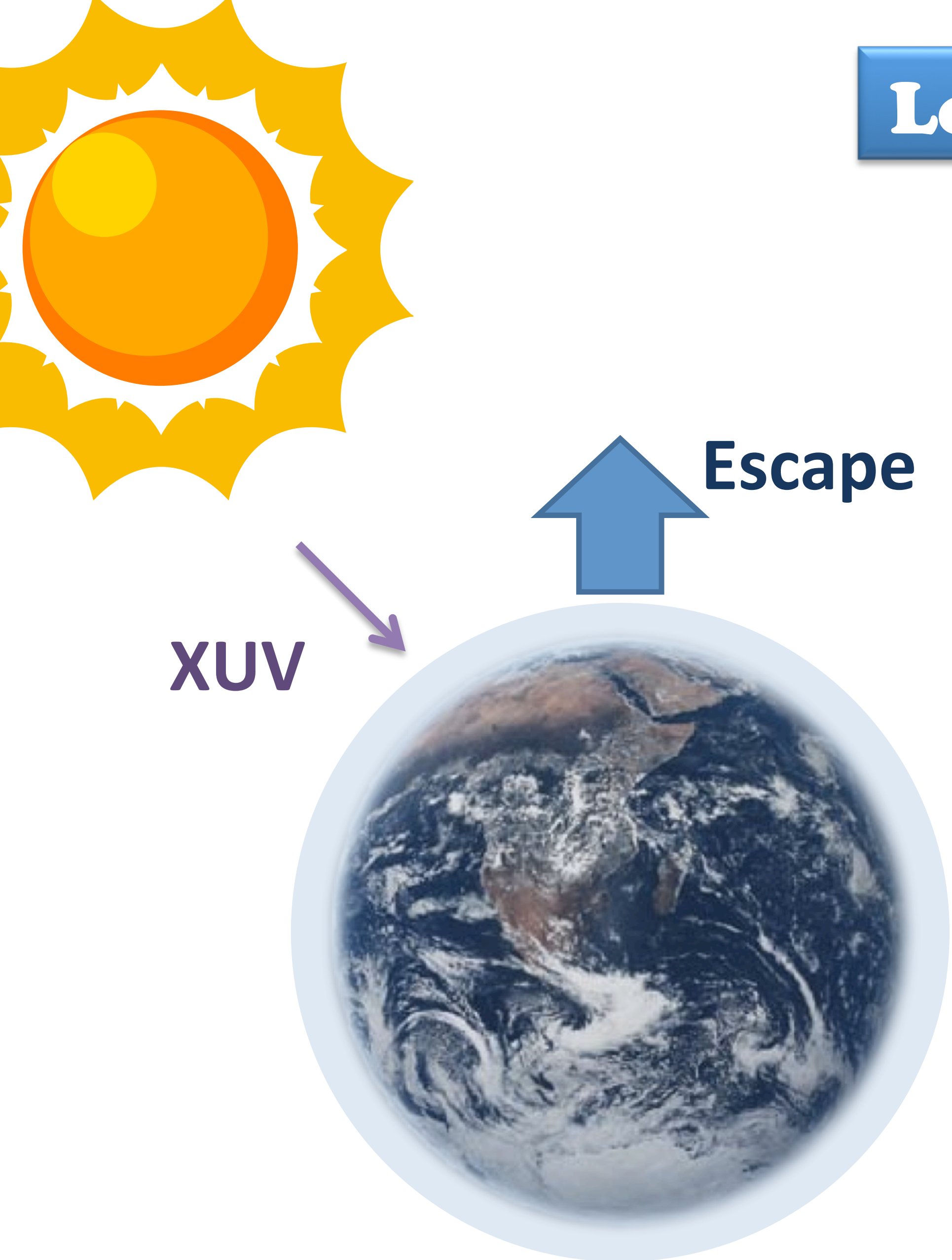


Close-In Super-Earths around M Stars

"escape" parameter: $\lambda = \dfrac{GM_p\mu}{kT_{disk}}$



Long-term Loss of Atmosphere



Mass-loss rate for energy-limited escape

incident UV flux

$$\dot{M} = \varepsilon \frac{3F_{\mathrm{UV}}}{4G\rho K}$$

efficiency

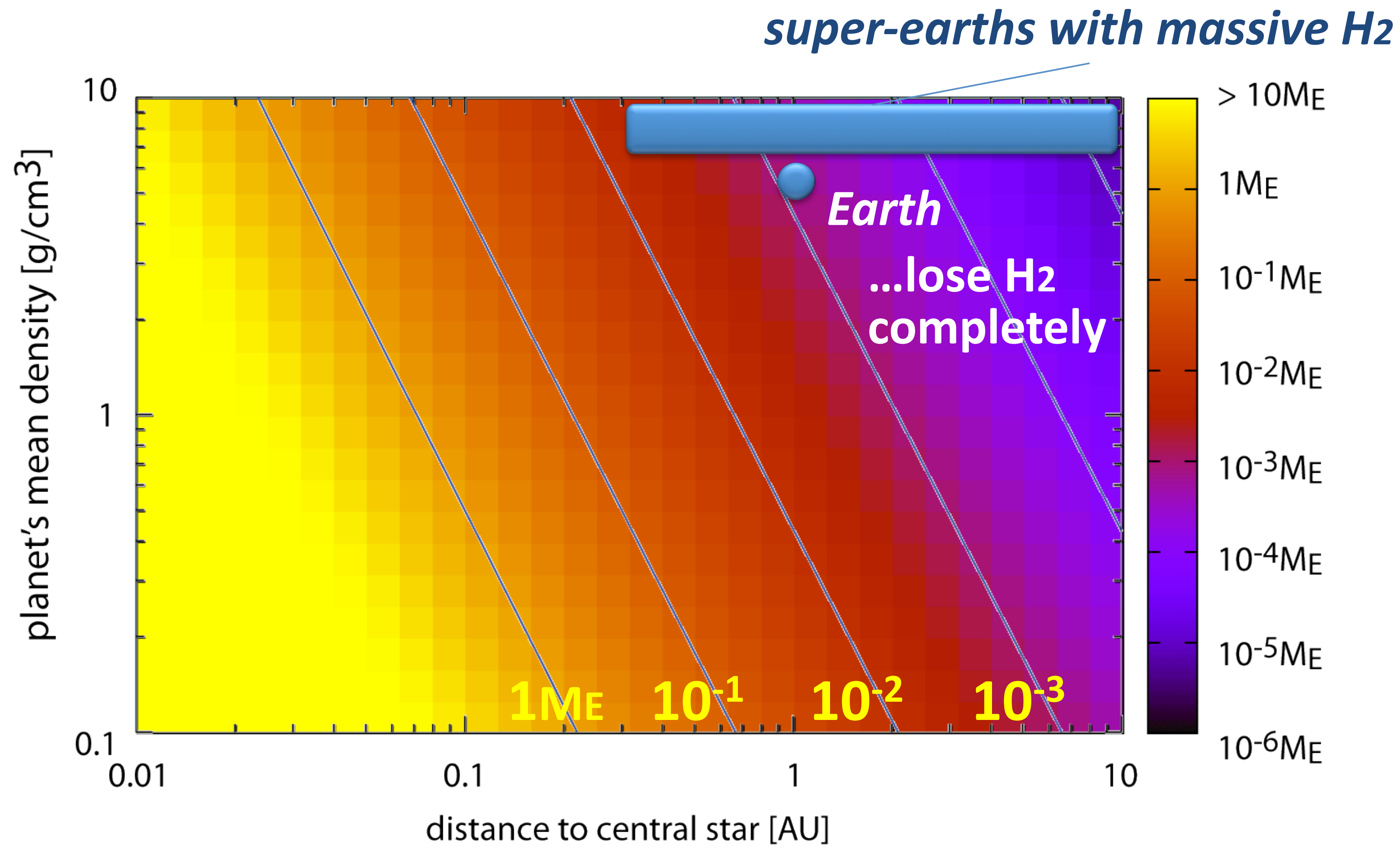
planet's density

Roche-lobe correction

ε = **0.4** (Yelle08 & many studies)

Long-term Loss of Atmosphere

Mass lost for 4 Gyr around G stars



Long-term Loss of Atmosphere

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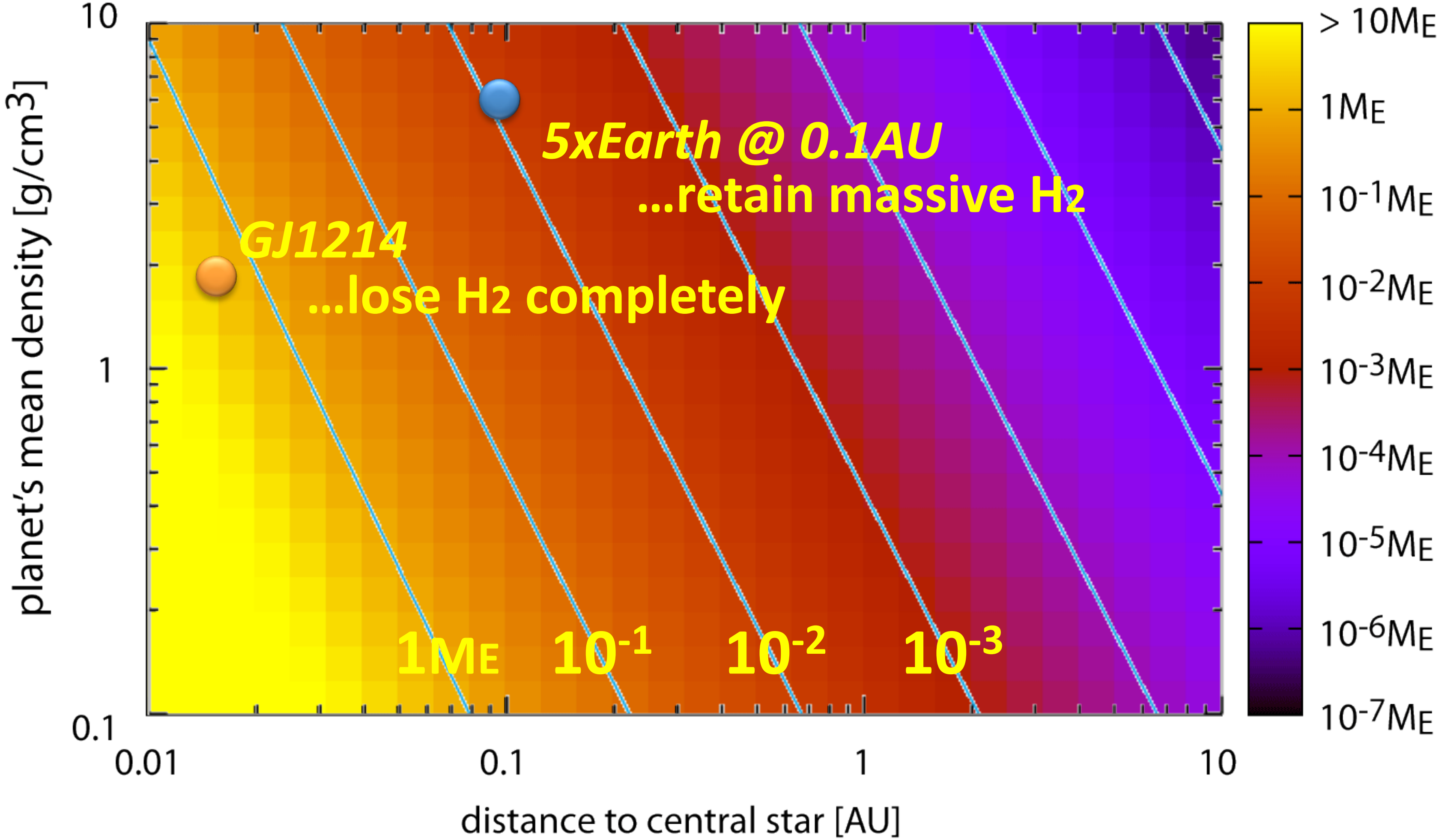
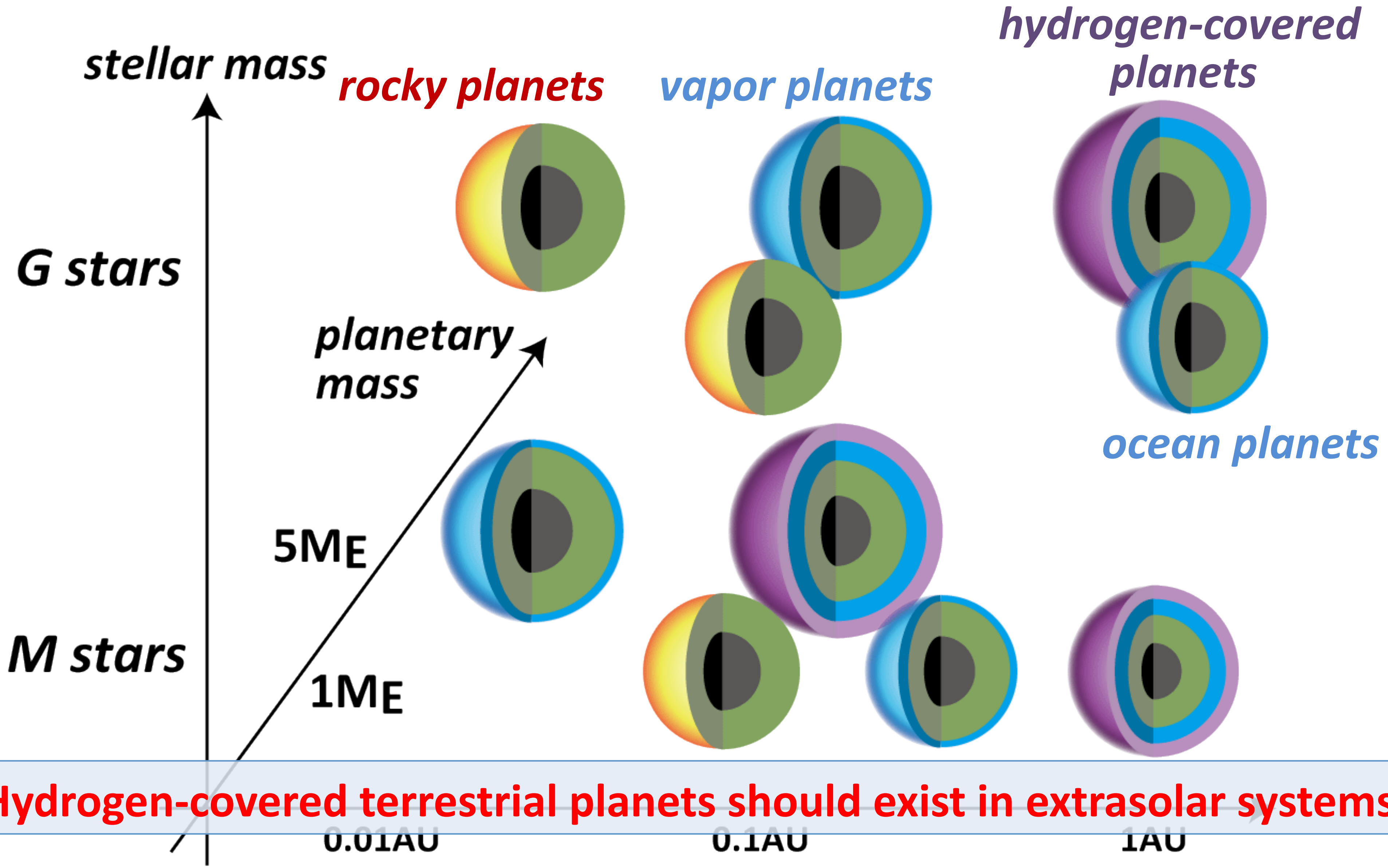


Summary: Terrestrial Planets to be Detected



Hydrogen-covered terrestrial planets should exist in extrasolar systems.

Ocean planets can be in-situ formed relatively easily.

Summary

- Recent theories of planet formation suggest that Earth-like planets are likely to form via giant collisions in a dissipating disk.

- While both deposition of accretion energy upon giant collisions and disk dissipation hinder the accumulation of the hydrogen atmosphere, a planet obtains a certain amount of hydrogen.

    - Earth-mass planets @ T_{disk}=280K obtains hydrogen comparable in mass to Earth's oceans.

    - The dependence on planet's mass is quite strong.

- Our study predicts:
    - Hydrogen-covered super-Earths should exist in extrasolar systems.
    - Ocean planets can be in-situ formed relatively easily.

- More studies are needed to bridge the gap between the solar system and extrasolar systems.